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Model development and analysis of a mid-sized hybrid fuel cell/battery vehicle with a representative driving cycle

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HIGHLIGHTS

- Model of mid-sized ICE vehicle is developed and validated.
- Model of hybrid FC/battery vehicle is built based on validated ICE vehicle model.
- Effect of driving pattern on performance is investigated using standard driving cycles.
- Driving cycle that represents the driving patterns in Amman city is developed experimentally.
- Performance of hybrid FC/battery vehicle found to be much better than the ICE version.

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ABSTRACT

Vehicles powered with internal combustion engines (ICEs) are one of the main pollutant sources in large cities. Most of large cities (*e.g.* Amman, capital of Jordan) suffer from frequent traffic jams. This leads to frequent stops and starts, and hence, an increase in tailpipe emissions. One way to minimize emissions is to use electric motors in the powertrain configuration. In this study, the performance of a hybrid fuel cell (FC)/battery vehicle is investigated utilizing different worldwide driving cycles. Initially, a model of a mid-sized ICE vehicle is developed and validated against experimental tests. The ICE vehicle validated model is then modified to be driven with only an electric motor powered by a hybrid FC/battery system. The effect of driving pattern, which varies from city to city and from region to region, is investigated. A driving cycle that represents the driving patterns in Amman city is developed based on experimental data and then used to evaluate the performance of both ICE and hybrid FC/battery vehicle configurations. It is found that the performance of the hybrid FC/battery configuration is much better than the ICE version in terms of emissions, fuel economy, efficiency, and speed tracking error.

1. Introduction

The transportation sector has a significant impact on both energy sustainability and the environment [1]. It was estimated that it contributes up to approximately 15% of the total global greenhouse gas emissions. Emissions from internal combustion engine (ICE) powered vehicles are the main pollutant source in urban areas [2]. Hence, many studies have been conducted in attempts to replace conventional energy sources by much cleaner ones such as electrical energy. In Amman city, the capital of Jordan, one of the main sources of air pollution is ICE vehicles. During the frequent traffic jams that occur at rush hours (refer to Fig. 1), there is a significant drop in engine efficiency along with an increase in tailpipe emissions.

The continuous escalation of oil prices along with the negative impact of burning conventional fuels on the environment have

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Fig. 1. The rush hours in one of Amman roads.

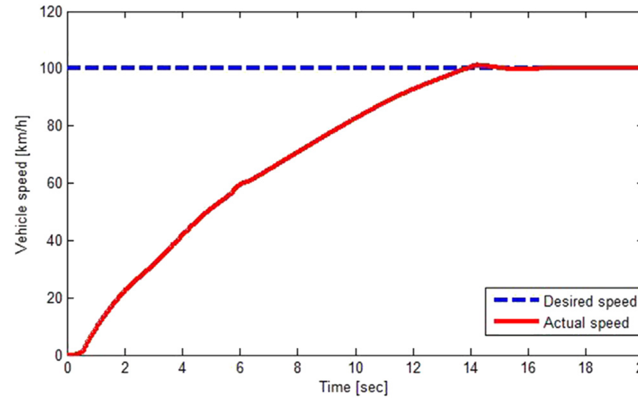

Fig. 3. Simulation result for the 0–100 [km h^{-1}] acceleration time.

motivated researchers worldwide to look for alternative energy sources and replacements for conventional fuels. The development of hybrid vehicles that are powered by both combustion engine and an electrical motor is considered to represent significant progress in the automotive industry due to its advantages of improving fuel efficiency and decreasing emissions.

In Ref. [3], the fuel economy of a series and parallel hybrid ICE/electric step van (with diesel engine) was compared with the fuel economy of a conventional step van using different driving cycles (*e.g.*, Central Business District bus cycles, New York City Cycle, US EPA City and Highway cycles). In Refs. [4,5] plug in electric vehicles that can be directly charged from the national grid were investigated and compared with ICE vehicles. Unfortunately, electrical vehicles usually have a limited range [3]. For longer ranges, a hybrid configuration can be adopted. Hybrid Fuel Cell (FC) vehicles are another promising alternative due to their cleaner operation, better performance, and higher energy efficiency than conventional vehicles [6]. The fuel economy of hybrid FC/battery vehicles was studied in Ref. [7] considering the initial and final status of battery state of charge (SOC). In Ref. [8], Abu Mallouh et al. developed a model for a hybrid FC/battery rickshaw using the PSAT software package. They carried out a comparison study between an ICE and a hybrid FC rickshaw and concluded that the fuel economy can be improved significantly in the hybrid FC configuration. The hybrid FC rickshaw model developed in Ref. [8] was used in Ref. [9] to investigate the performance with a fuzzy logic control strategy that controlled the power distribution of a hybrid FC/battery rickshaw.

It is essential to quantify the amount of emissions and fuel consumption by using a driving cycle that represents actual driving patterns. Representative driving cycles are also essential when designing and analyzing powertrains and energy management systems of electrical and hybrid vehicles. In Ref. [10], a methodology was proposed to understand the relation between battery performance and driving cycles of electric and hybrid vehicles operating in real-world situations. In Ref. [11], the impact of real-world driving patterns on energy and power requirements of a converted plug-in hybrid electric vehicle was investigated. In Refs. [12,13], the driving cycle effect on fuel cell performance and microstructure of the membrane electrode assembly was investigated to predict the life time of the cell. In Ref. [14], it was concluded that the fuel economy of a hybrid FC/battery configuration depends directly on recovering braking energy and therefore depends on the driving cycles.

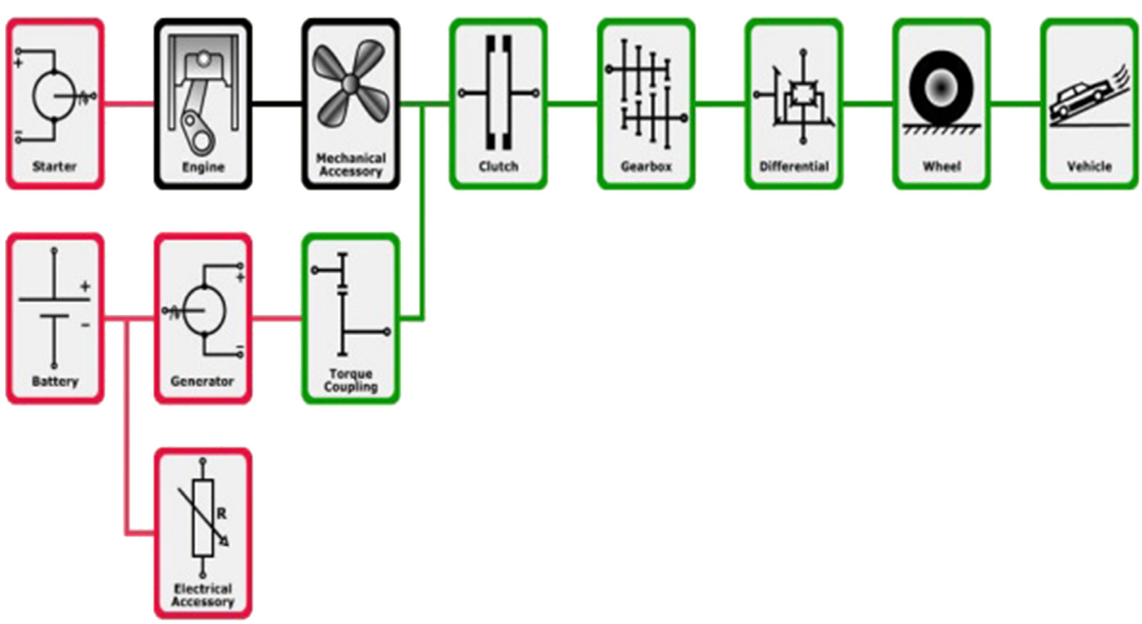

Fig. 2. PSAT model configuration for an ICE vehicle.

Table 1
Main specifications of Nissan Sunny EX.

Engine type	1.6 L 4-cylinder
Max. power (kW)	78 @ 6000 rpm
Max. torque (Nm)	146 @ 3500 rpm
Tire size	175/70R14
Maximum speed (km h^{-1})	185
Fuel capacity (L)	55
Curb weight (kg)	1180
Acceleration time for 0–100 km h^{-1} (s)	14
Seating persons	5
Overall length (cm)	451.0
Overall width (cm)	171.0
Overall height (cm)	144.0
Drag coefficient	0.42
Frontal area (m^2)	1.82

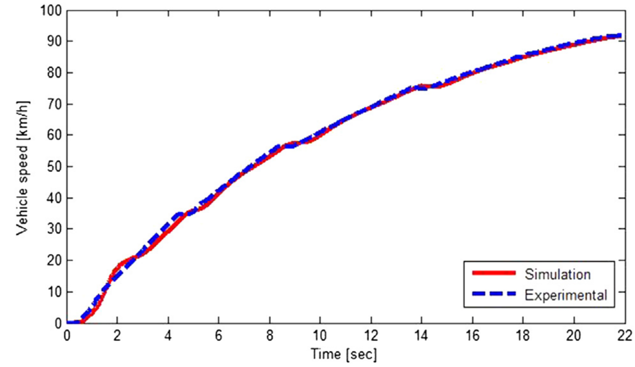

Fig. 5. Velocity responses for ICE vehicle.

Jordan officially has no existing driving cycles to represent traffic and driving patterns. In this study, a driving cycle for Amman city, the capital of Jordan, is developed to analyze the characteristics of vehicles' driving patterns and to quantify fuel consumption and emissions for both ICE and hybrid FC/battery vehicles. It should be noted that to our knowledge, this study presents the first development of Amman driving cycle. The effect of driving pattern on the vehicle performance is studied using the Amman driving cycle and four other worldwide cycles from the literature. The main objective of the study is to investigate the performance of a mid-sized hybrid FC/battery vehicle in comparison with the ICE version of the same vehicle. A model of an ICE powertrain is first developed using the Powertrain System Analysis Toolkit (PSAT) software package and then validated against experimental acceleration data. The developed model is then utilized to design a model of a hybrid FC/battery vehicle. In this study, it is shown that the hybrid FC/battery version has zero emission and a better fuel economy when compared with the ICE version.

2. Development and validation of ICE vehicle model

As mentioned earlier, the main source of pollution in Amman city, the capital of Jordan, is caused by the transportation sector. In this sector, taxis are considered to be the principle pollutant source in Amman city due to their large number and driving behavior. In Amman city, taxis usually pick up passengers off the roads and not by phone orders. Most of the taxis do not work in fixed routes but rather work in any road according to the customer desire and final destination. One of the most common taxi vehicles in Amman is Nissan Sunny. Consequently, a model for this brand of taxis is developed for this study. Performance results of the ICE vehicle model are used as a benchmark when compared to the hybrid version of the vehicle.

The PSAT software package is used to develop a model for an ICE powered vehicle (refer to Fig. 2). This model is tested and validated by three tests. In the first test, the time required for the vehicle model to accelerate from 0 to 100 km h^{-1} is measured. This time period is found to be 14 s as shown in Fig. 3, and is found to match the acceleration time value listed in Table 1 for the Nissan Sunny. In the second test, the maximum speed the vehicle model can reach is investigated. This speed is found to be 185 km h^{-1} as indicated in Fig. 4. This value of maximum speed is found to be in a good agreement with the value shown in Table 1. For the third test, experimentally collected data is used to validate the dynamic behavior of the ICE vehicle model. The data is recorded from experimental tests conducted on a real Nissan Sunny taxi. A G-TECH/Pro RR accelerometer was installed in the testing vehicle and then calibrated in order to record its velocity, engine revolutions per minute, power, and acceleration. During the real-time test, which is performed along a flat straight ground, the vehicle accelerated from rest and traveled along a known distance under normal driving behavior. This procedure is repeated several times and the average values are recoded. The ICE vehicle model is tested using the same experimental procedure. Fig. 5 shows a good match between the experimental and simulation vehicle speed results. From Figs. 6 to 8, a good match is shown between the experimental and simulation responses for engine speed, torque at wheels, and power at wheels, respectively.

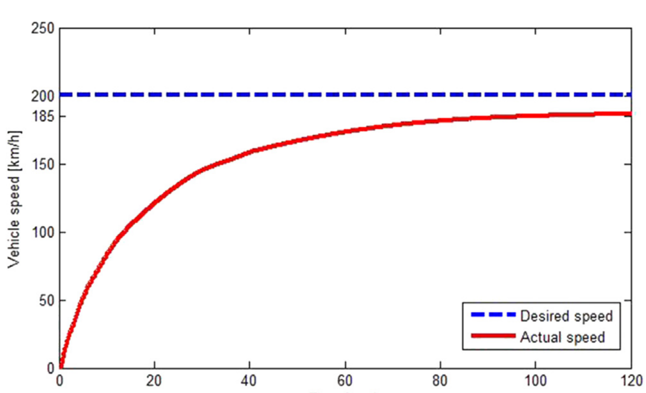

Fig. 4. Simulation result for the maximum speed.

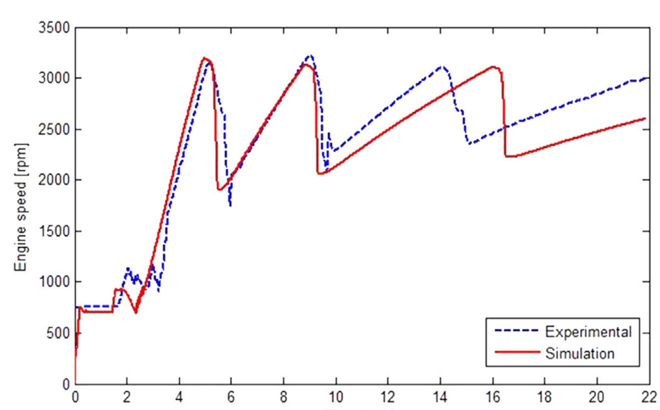

Fig. 6. Engine speed responses for ICE vehicle.

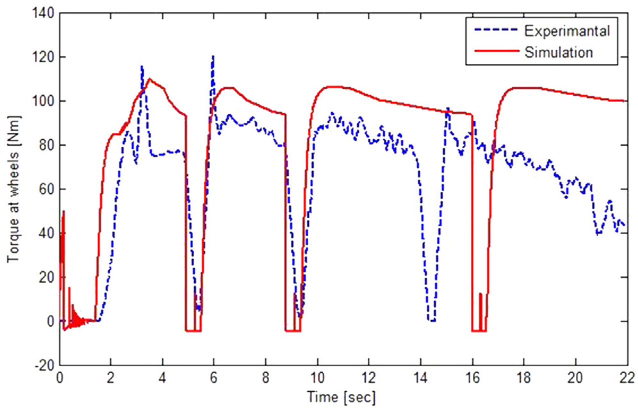

Fig. 7. Torque at the wheels responses for ICE vehicle.

Table 2
Parameter values of some standard driving cycles.

Parameter	NY city	Indian urban	Japan 10	France INRETS urban
Time (s)	598.0	1244.0	135.0	559.0
Distance (km)	1.9	10.6	0.7	3.5
Maximum speed (km h^{-1})	44.3	90.0	49.0	57.2
Average speed (km h^{-1})	11.3	31.1	17.6	22.3
Maximum acceleration (m s^{-2})	2.7	1.5	0.8	2.2
Average acceleration (m s^{-2})	0.6	0.6	0.7	0.7
Maximum deceleration (m s^{-2})	−2.6	−1.4	−0.8	−2.1
Average deceleration (m s^{-2})	−0.6	−0.8	−0.7	−0.6
Number of stops	18.0	13.0	2.0	5.0
Stops duration (s)	210.0	388.0	39.0	138.0
Number of stops per km	10.0	1.0	3.0	1.0
Stop duration (s) per km	110.5	36.6	55.7	39.4

3. Development of Amman driving cycle

A driving cycle can be defined as a sequence of vehicle operating conditions (*i.e.*, idle, acceleration, cruising, and deceleration) in a certain environment [8]. Driving cycles are used to measure the performance of vehicles in terms of emissions and fuel consumption. Driving patterns vary from city to city and from region to region. Many driving cycles have been developed worldwide utilizing different methodologies. The summary of the most widely adopted driving cycles can be found in Ref. [15].

Table 2 lists the specifications of some of the worldwide driving cycles of light duty vehicles such as New York city cycle, developed by the Environmental Protection Agency of the United States, Indian urban cycle [16], Japan 10 mode urban cycle, developed by Japan Automobile Standards Internationalization Center, and France urban cycle, developed by French National Institute for Transport and Safety Research. As presented in Table 2, there are significant differences between the driving cycle specifications, in terms of speed, acceleration, deceleration, number of stops, and cycle duration. Driving cycles are designed to represent driving patterns in certain cities. As driving patterns vary from city to city and from region to region, the available driving cycles obtained for certain cities or countries are not usually applicable for other cities or countries. Therefore, there has been considerable work by researchers to develop driving cycles for certain cities and regions.

Authors of Ref. [17] analyzed the driving characteristics and developed driving cycles for some Chinese cities. The driving cycles were compared with European and American driving cycles where the data recorded were adjusted by the traffic adjustment factors to reflect the overall traffic. The results of the comparison with the European and US cycles suggest that the European or US emission factors could be significantly different from those of Chinese cities (*i.e.*, the driving cycles of China). In Ref. [18], the authors developed a standard driving cycle in the urban areas of Hong Kong. On-road speed time data were recorded along two routes. It was found that none of the developed driving cycles in the literature (*i.e.*, US 75, Perth cycle, and Melbourne peak cycle) satisfactorily described the driving characteristics in Hong Kong. The development of two driving cycles for a motorcycle and a light-duty vehicle in Hanoi-Vietnam was carried out in Ref. [19]. The data recorded was analyzed to characterize the typical driving patterns. The driving cycles were developed by a random selection process to match the overall summary statistics. They concluded that the developed driving cycles are the first set of driving cycles for Hanoi.

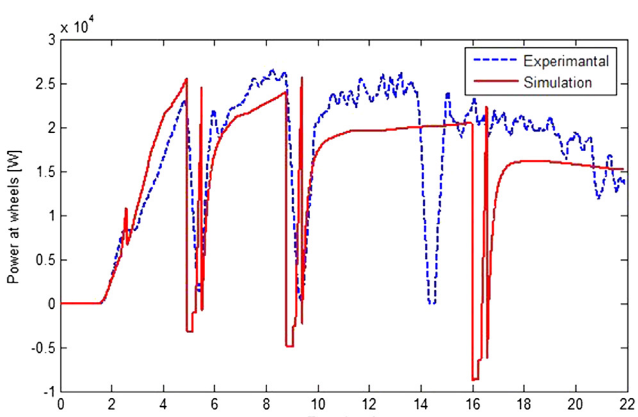

Fig. 8. Power at the wheels responses for ICE vehicle.

In Ref. [20], the author conducted comprehensive analyses to develop a set of driving cycles, using a quite large and unique database that describes actual driving conditions in Europe. Sixty European private cars were selected in France, UK, and Germany to represent the corresponding in-use car fleet. The authors of Ref. [21] developed a driving cycle for Bangkok during peak periods. Comparisons listed in the study showed that the driving parameters of the developed driving cycle are much closer to those obtained from the real-world measured data than those calculated from the presently-used European driving cycles. This implies that the developed driving cycle produces more realistic results for vehicles traveling in Bangkok in terms of emissions and fuel consumption.

In general, there are two types of driving cycles; transient and steady-state. In the steady-state type of cycle, the driving pattern is straight lines at near constant speed and does not capture the transient behavior during actual driving. This approach artificially boosts the fuel economy and reduces vehicle emissions. On the other hand, the transient type of cycle represents the real dynamics associated with the actual vehicle such as acceleration, deceleration, and fast perturbations around the desired speed. By utilizing this type, more accurate emission and fuel economy results can be obtained. Thus, a transient-type driving cycle is developed for Amman city. A comprehensive review of existing methodologies and practices for developing driving cycles is presented in Ref. [22].

For this study, driving data for a light duty vehicle (taxi) was recorded while traveling through Amman urban areas. Taxies were chosen to provide coverage of a range of driving conditions seen on Amman city roads. Specifically, a G-TECH/Pro RR Fanatic High-Frequency GPS device was installed in two Nissan Sunny taxies to record vehicle velocity and distance traveled. Data was recorded during both peak and light hours of traffic. 20 data sets were recorded for a total of 13.4 h of data and a cumulative travel

Table 3
Parameters of recorded data sets.

Data set	Distance (km)	Max. speed (km h^{-1})	Average speed (km h^{-1})	Average acceleration (m s^{-2})	Average deceleration (m s^{-2})	Number of stops	Stop duration (s)	Number of stops/km	Stop duration (s)/km
1	15.7	77.8	23.4	0.6	−0.7	36	708	2	45.2
2	16.6	95.7	24.8	0.6	−0.7	35	810	2	48.7
3	16.9	81.6	25.3	0.6	−0.6	35	594	2	35.1
4	10.9	70.5	16.3	0.6	−0.6	51	656	5	60.0
5	11.4	67.9	17.0	0.6	−0.6	28	857	3	75.3
6	28.3	105.5	42.2	0.4	−0.5	15	465	1	16.4
7	19.9	79.0	29.7	0.5	−0.6	19	282	1	14.2
8	25.1	103.0	37.5	0.6	−0.7	17	437	1	17.4
9	15.3	77.5	23.0	0.5	−0.6	17	938	1	61.1
10	21.7	85.3	32.4	0.5	−0.5	14	301	1	13.9
11	15.2	72.0	22.6	0.5	−0.6	34	515	2	34.0
12	13.2	77.4	19.8	0.4	−0.5	19	1030	1	77.8
13	17.8	114.3	26.6	0.6	−0.7	29	671	2	37.7
14	16.7	76.5	24.9	0.5	−0.6	35	496	2	29.8
15	18.0	87.2	26.9	0.4	−0.5	12	943	1	52.3
16	23.7	91.6	35.4	0.5	−0.6	32	443	1	18.7
17	16.1	89.2	24.0	0.6	−0.7	35	743	2	46.3
18	21.5	94.0	32.2	0.5	−0.6	19	504	1	23.4
19	9.5	68.4	14.2	0.6	−0.6	45	1016	5	106.5
20	15.3	95.1	22.8	0.6	−0.7	37	714	2	46.7
Mean	17.4	85.5	26.1	0.5	−0.6	28	656	2	43.0

distance of 348.8 km. The statistics for the recorded data are presented in Table 3 where each data set is about 40 min long (*i.e.*, 2410 s). The mean of each parameter is presented at the bottom of the table. The variation in the data is illustrated by the low and high values for the key parameters: maximum speed from 67.9 to 114.3 km h^{-1}, average speed from 14.2 to 42.2 km h^{-1} and number of stops from 1 to 5 stops per km.

From Table 3, data sets 6 and 19 are taken to represent the cases of light and peak traffic conditions, as illustrated in Figs. 9 and 10, respectively. As expected, the vehicle speed in the light traffic condition is higher than that in the peak traffic condition. From Fig. 9, it is seen that the speed distribution is concentrated in the middle region of speed. By contrast in Fig. 10, the vehicle speed distribution is shifted towards the low speed region.

Figs. 11 and 12 show a three-dimensional normalized histogram for light and peak traffic conditions, respectively. Each bar in the histogram represents the duration of various acceleration levels at specific vehicle speeds. From Figs. 11 and 12 it is again seen how the traffic conditions (*i.e.*, light and peak) have a big impact on the driving patterns in terms of vehicle speeds and accelerations. In Fig. 11, the histogram bars are concentrated in the middle of the speed range. Where as in Fig. 12, the bars are close to the low speed region.

In this paper, the approach introduced in Ref. [23] was adopted to develop the driving cycle for Amman city. The basic approach is to select a data set (from the sets presented in Table 3) whose characteristics are most similar to those of all the recorded driving data. This approach can be summarized in the following steps: (1) calculate the mean values of all recorded driving data, (2) derive factor scores for each data set utilizing the factor analysis method in statistics, (3) find the smallest Euclidean distance between the driving data calculated in step 1 and each other driving data utilizing the factor scores derived in step 2. It should be noted that the Euclidean distance computation is performed to find out the dissimilarity between all recorded driving data. Figs. 13–15 are used to illustrate the driving cycle that was developed for Amman using this approach.

In Fig. 13, the speed distribution and its accumulation for the Amman driving cycle are presented. It is clear that 75% of the speed distribution of the Amman driving cycle is below 40 km h^{-1}. On the

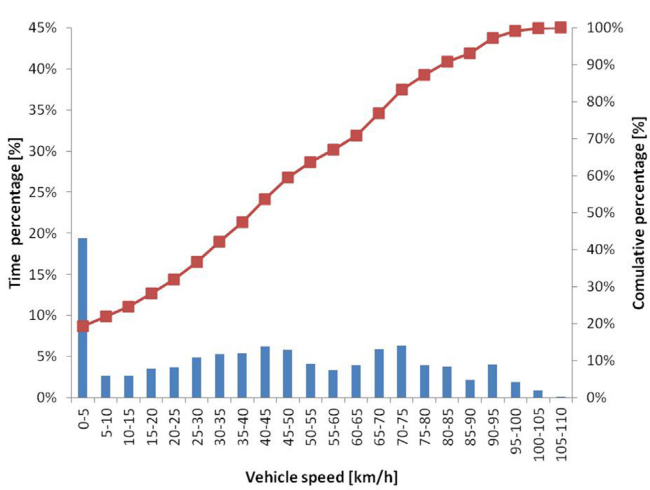

Fig. 9. Speed distribution and its accumulation for light traffic conditions.

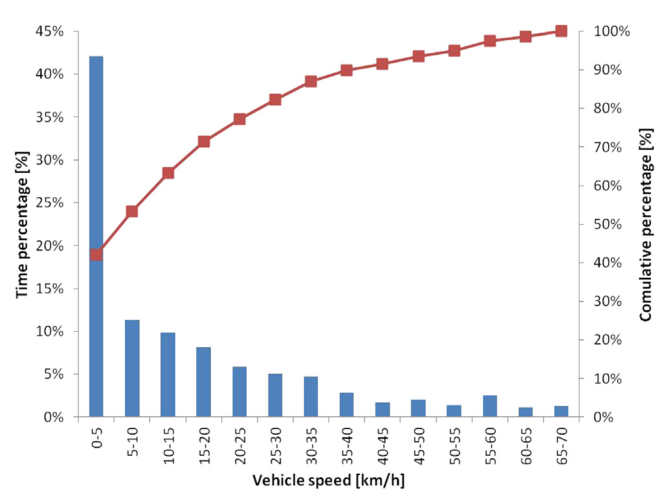

Fig. 10. Speed distribution and its accumulation for peak traffic conditions.

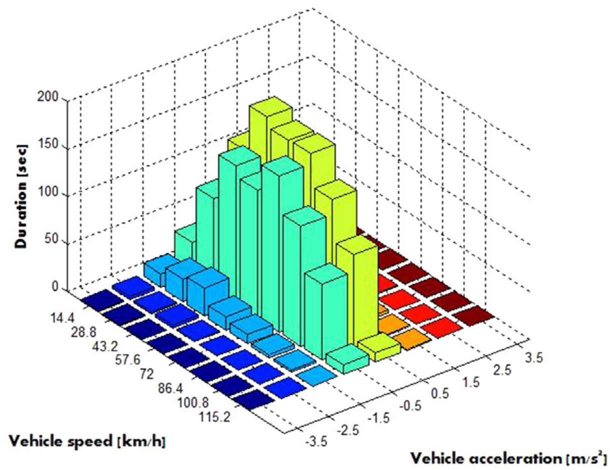

Fig. 11. Speed–acceleration density for light traffic conditions.

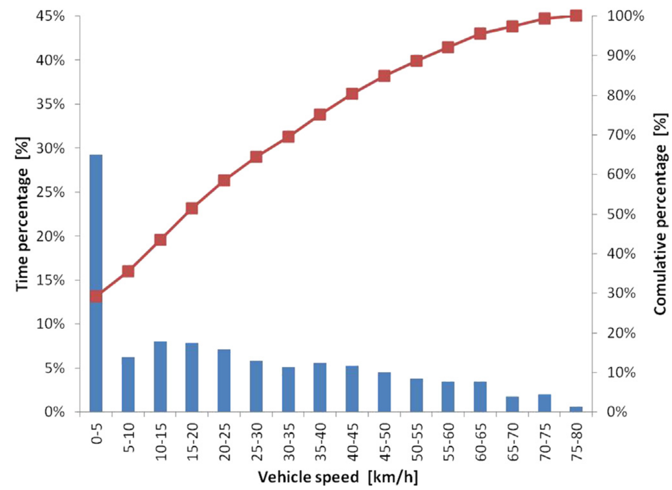

Fig. 13. Speed distribution of the developed Amman driving cycle.

other hand, Fig. 14 shows the transient nature of the Amman driving cycle that has frequent stops, accelerations, and decelerations. Fig. 15 shows the speed–acceleration density of the developed Amman driving cycle and Table 4 summarizes the statistics. When comparing the developed Amman driving cycle with the ones listed in Table 2, it is clear that the maximum speed of the Amman driving cycle is higher than its peer in all the listed driving cycles except the one in the Indian driving cycle where it is 90 km h^{-1}. The average speed of the Amman driving cycle is close to that seen in the France driving cycle. On the other hand, the average acceleration of the Amman driving cycle is equal to the accelerations in the NY and Indian driving cycles. However, the number of stops per km for the Amman driving cycle is different from the number of stops for all other driving cycles. The total stopping time per km of the Amman driving cycle is higher than the times for the France and Indian driving cycles and less than the times for the NY city and Japan driving cycles. Thus, the developed Amman driving cycle is unlike any of the other driving cycles introduced in the literature (refer to Table 2 for more details).

The ICE vehicle model was tested using the Amman driving cycle and all driving cycles presented in Table 2. Performance results are presented in Table 5. It was found that the fuel economy with Amman driving cycle is 8.92 L/100 km, which is about the actual fuel economy the taxis driver recorded. As expected, the powertrain efficiency is relatively low (*i.e.*, 18.33%). This low efficiency is mainly due to the stop and start characteristics of the Amman driving cycle. In addition, the emissions value is recorded to be 211.1 g km^{-1}. From Table 5, one notes that the fuel economy and other performance parameters of the ICE vehicle with the Amman driving cycle is different from the values for the other driving cycles listed in Table 5. Thus, it is concluded that this justifies the development of a unique driving cycle for Amman city.

4. Development of hybrid fuel cell/battery vehicle model

Fuel cells are electrochemical devices that are used to directly convert chemical energy into electrical energy. The Proton Exchange Membrane (PEM) fuel cell is the fuel cell type that is most commonly used in hybrid vehicles due to its simplicity, viability, quick start up, higher power density, and lower temperature operation [24]. However, a standalone nominally sized FC system is typically unable to respond to the required power demand during start-up and transient events. As a result, an over-sized FC system, to ensure adequate response to transient power demand, is typically used. As a consequence, the cost of the system increases. To avoid this increase in the cost, the FC is usually downsized and hybridized with another energy storage system [25]. Hybrid FC/

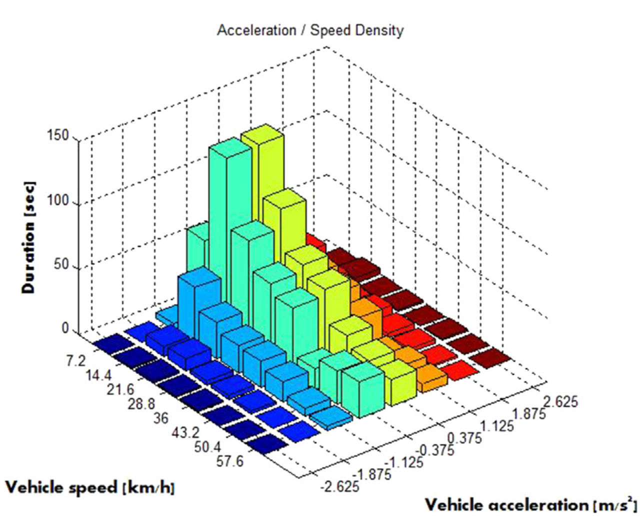

Fig. 12. Speed–acceleration density for peak traffic conditions.

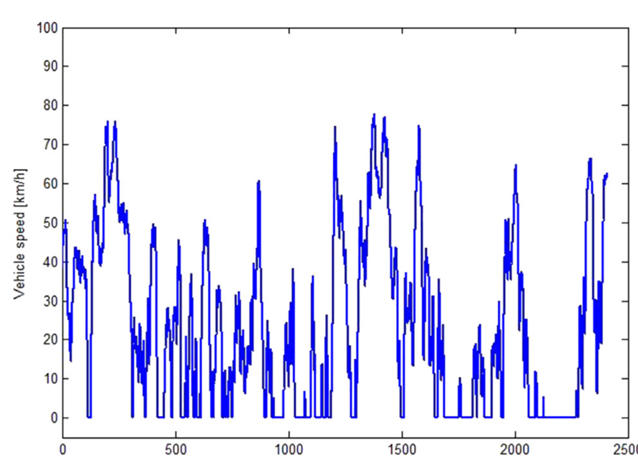

Fig. 14. Developed Amman driving cycle.

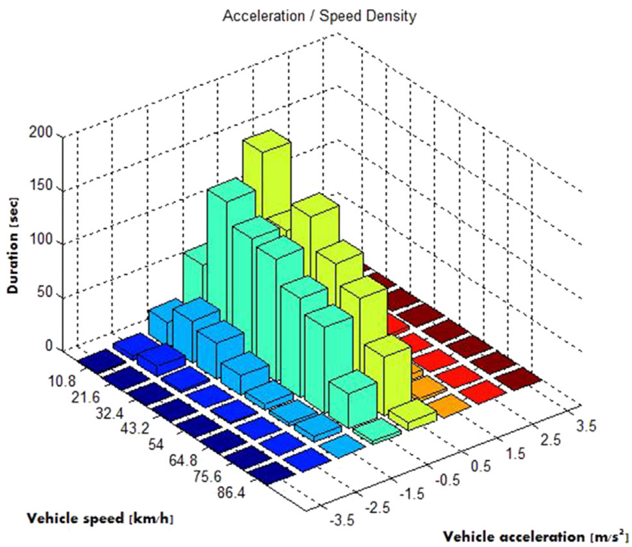

Fig. 15. Speed–acceleration density of the developed Amman driving cycle.

battery powertrains consist of an electrical motor, a fuel cell, and electrical energy storage units, such as batteries and ultra capacitors. The electrical energy storage units operate only under certain conditions. In this study, the main power source used to drive the electrical motor is the fuel cell. The battery system is only used when the power produced by the fuel cell is insufficient to drive the motor during sudden acceleration.

Lead–acid battery types were widely used during the early stages of electric vehicle development. However, such batteries have high weight/energy density ratios and hence vehicles weights were high due to the need for large number of batteries [26]. In addition, due to high degradation ratios in lead–acid batteries, the performance of early electric vehicles was limited in terms of both speed and range. As a result, more advanced battery technologies were needed to offer significant improvements in performance such as nickel metal hydride (Ni-MH) and lithium-ion (Li-ion) batteries. Ni-MH batteries used to have an edge over Li-ion batteries in terms of production readiness and cost [25]. In recent years, a number of the major automakers have switched to Li-ion batteries because of their high energy density, light weight and good cost compared to Ni-MH batteries. However, Li-ion batteries have less life time and limited range of working temperature when compared to Ni-MH batteries.

The operating conditions of hybrid FC/battery vehicles mainly determine the type of electrical motor to be used in the powertrain. Different kinds of electrical motors can be used such as AC induction motors, DC brushless or brushed motors. The AC induction motors produce high torque under low speed conditions and can operate at high speeds as well [8]. They are less efficient and have lower power/weight ratios than DC brushless motors. On the other hand, the DC brushless motors are costly but offer a high power/weight ratio. However, both motors are of low cost when compared with DC brushed motors for a given torque and power requirement. Although the DC brushed motors are much easier to operate and control than the other two types of motors, they have low power/weight ratios.

The basic design approach in this study is that the hybrid FC/battery vehicle must be competitive with ICE vehicle in terms of drivability and performance. In terms of drivability, the hybrid FC/battery vehicle must be able to accelerate from 0 to 100 km h^{-1} in 14 s, has a top speed of at least 120 km h^{-1}, and be capable of tracking the Amman driving cycle with minimum trace error. In terms of performance, the FC/battery hybrid vehicle must have significantly better fuel economy and overall system performance, good recovery of braking energy and very low emissions when compared with the ICE vehicle. In addition, it is important that the hybrid FC/battery vehicle be able to maintain the battery at required SOC without usage of external electrical power source (power plug). The power management control strategy adopted in this study is called load following strategy. In this strategy, the FC provides the motive power under normal driving conditions and the battery boosts power under transient conditions and when it is needed. It should be noted that the Ni-MH batteries are recommended in hybrid systems when they are not the main power supply [27]. Thus, Ni-MH batteries with 6.5 Ah and 1.2 V capacity per cell were selected in the proposed hybrid powertrain model.

One of the most important factors in hybrid FC/battery vehicle design is the sizing (hybridization degree) of the FC and the battery systems. In Ref. [28], the sizing of the FC and battery was based on maximizing the efficiency of the hybrid FC/battery vehicle. The optimal hybridization degree was studied in Ref. [29] and it was found that the vehicle type and driving cycle affect directly the hybridization degree. The fuel cell is the most critical and most costly component in any hybrid system, so it must be sized carefully. To seek for the best match and optimum performance for the hybrid FC/battery vehicle model in comparison with the developed ICE vehicle model, different capacity combinations of battery and fuel cells were investigated as shown in Table 6. The number of battery cells was varied from 0 to 180 cells while the fuel cell capacity was varied from 20 kW to 80 kW. Note that zero battery cells represent vehicle powered by FC only. The electrical motor is selected as a brushless DC motor with 36 kW continuous power, 80 kW peak power, and 90% efficiency. It was found that the 36 kW continuous power is the amount of power needed to satisfy the average power requirement of the vehicle during the Amman driving cycle. It should be noted that the peak power may be

Table 4
Parameters of the developed Amman driving cycle.

Parameter	Value
Time (s)	2410
Distance (km)	15.7
Maximum speed (km h^{-1})	77.8
Average speed (km h^{-1})	23.4
Average acceleration (m s^{-2})	0.6
Average deceleration (m s^{-2})	−0.7
Number of stops	36.0
Stops duration (s)	708.0
Number of stops per km	2
Stop duration (s) per km	45.2

Table 5
Performance of the ICE vehicle with different driving cycle.

Driving cycle	Amman	Indian urban	New York urban	Japan 10	France INRETS urban
Fuel economy gasoline (L/100 km)	8.92	6.38	10.86	7.19	9.96
Time the trace is missed by 2 mph (%)	4.54	0.15	2.31	0	3.65
Absolute average difference on vehicle speed (km h^{-1})	0.89	0.55	0.69	0.56	0.88
Initial SOC%	70	70	70	70	70
Final SOC%	69.7	69.55	69.44	69.48	69.34
Powertrain efficiency (%)	18.33	17.16	14.87	15.91	17.29
Percentage braking energy recovered at battery (%)	0	0	0	0	0
CO_2 emission (g km^{-1})	211.1	151.0	256.9	170.1	235.7

Table 6
Drivability and performance simulation results of hybrid FC/battery vehicle model with different combination of FC and battery capacities.

No. of battery cells	0 battery cells				60 battery cells				120 battery cells				180 battery cells			
FC (kW)	20	40	60	80	20	40	60	80	20	40	60	80	20	40	60	80
Fuel economy gasoline equivalent (L/100 km)	5.09	5.20	5.21	5.24	5.04	4.89	4.90	4.94	4.71	4.58	4.59	4.63	4.54	4.44	4.46	4.5
Time missed by 2 mph (%)	8.04	1.52	1.00	1.00	2.44	1.04	0.99	0.98	1.29	0.99	0.97	0.97	1.00	0.98	0.97	0.97
Vehicle speed error (km h^{-1})	0.93	0.34	0.30	0.30	0.44	0.32	0.31	0.31	0.34	0.31	0.31	0.31	0.32	0.31	0.31	0.31
Initial SOC %	NA	NA	NA	NA	70	70	70	70	70	70	70	70	70	70	70	70
Final SOC %	NA	NA	NA	NA	54.4	71.1	73.8	74	63.6	72.7	74.5	74.6	66.3	72.3	73.6	73.7
Powertrain efficiency (%)	38.9	40.3	40.5	40.3	39.2	42.0	42.1	41.9	42.1	44.6	44.8	44.5	43.6	45.8	45.9	45.6
Braking energy recovered (%)	0	0	0	0	50.2	49.0	48.5	48.4	62.7	61.9	61.7	61.6	67.0	66.6	66.5	66.5
Maximum speed (km h^{-1})	99.6	121	122	122	100	122	122	121	100	122	122	122	100	122	122	122
Time to reach 100 km h^{-1} (s)	34.0	31.3	19.4	14.8	49.3	23.6	16.6	13.4	30.8	19.2	14.7	12.7	23.2	16.5	13.3	12.7
CO_2 emission (g km^{-1})	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

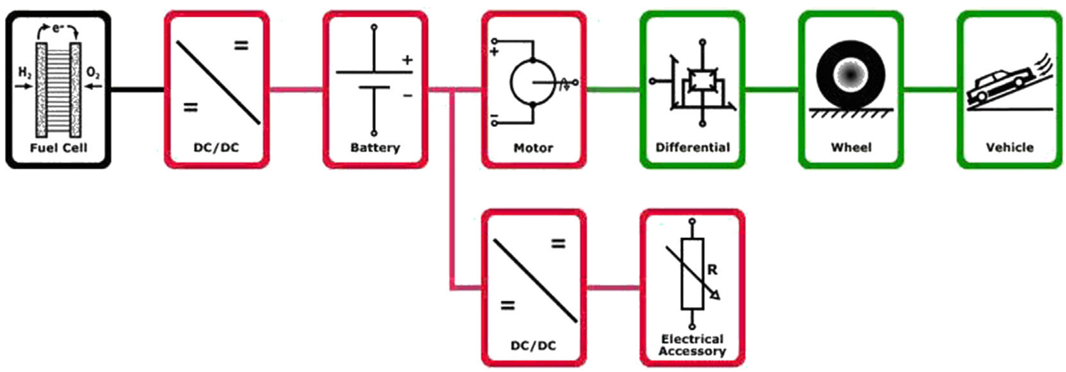

Fig. 16. PSAT model configuration of hybrid FC/battery vehicle.

reached occasionally for a short period during acceleration. The software package PSAT was utilized to develop the hybrid FC/battery vehicle model as shown in Fig. 16. The simulation results for all FC and battery capacity combinations are presented in Table 6. From Table 6, it is clear that the FC only vehicle model (*i.e.*, zero battery cells) is able to satisfy the 0–100 km h^{-1} target, maximum speed requirement and successfully track of the Amman driving cycle, only with a FC with a 80 kW power capacity. The disadvantages of this model are the large size of FC stack (*i.e.*, more cost), no braking energy recovered, and low fuel economy as well as only moderate system efficiency. Thus, the hybrid FC model with battery is expected to perform better. In terms of performance requirements only, there are two FC/battery candidate combinations: 40 kW FC with 120 battery cells and 40 kW FC with 180 battery cells. These two combinations have relatively similar performance in terms of fuel economy, maintaining SOC around 70% at the end of the driving cycle, system efficiency, and percentage of recovered braking energy. However, both models failed when it comes to the 0–100 km h^{-1} requirement. Thus, the hybrid FC vehicle model with 60 kW FC capacity and 120 battery cells was chosen as the optimum choice that satisfies all requirements. It is important to mention that if the 0–100 km h^{-1} requirement is relaxed, one may go with lower capacities for FC and battery which is useful in terms of reducing cost and weight.

Fig. 17 shows the vehicle speed response of the hybrid FC model with 60 kW FC stack and 120 battery cells and with the Amman driving cycle. It is clear that the desired velocity is tracked successfully. Fig. 18 shows the simulation results of the motor, FC, and battery power responses for the first 100 s of the Amman driving cycle. From Fig. 18, it is clear how the control strategy works, where

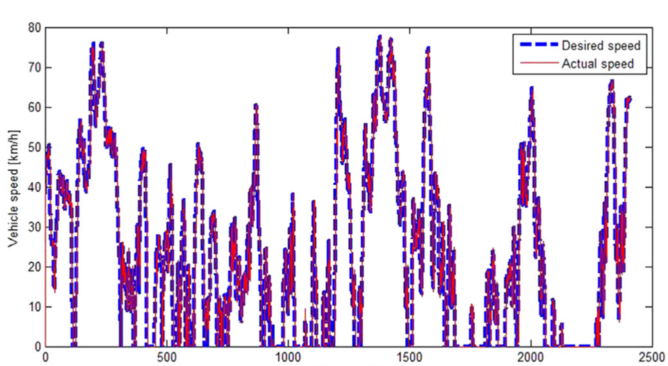

Fig. 17. Vehicle speed of hybrid model with 60 kW FC and 120 battery cells.

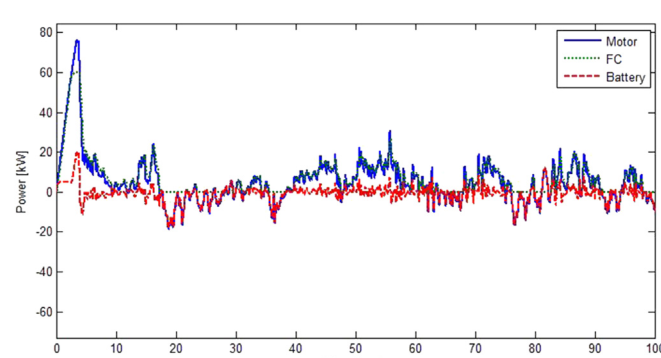

Fig. 18. Power responses for motor, FC, and battery with 60 kW FC and 120 battery cells.

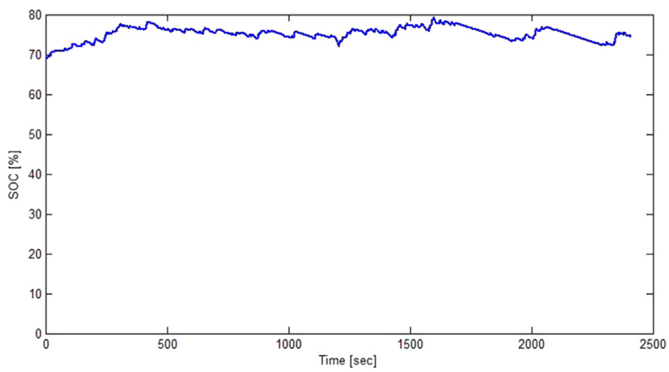

Fig. 19. Battery SOC with Amman driving cycle.

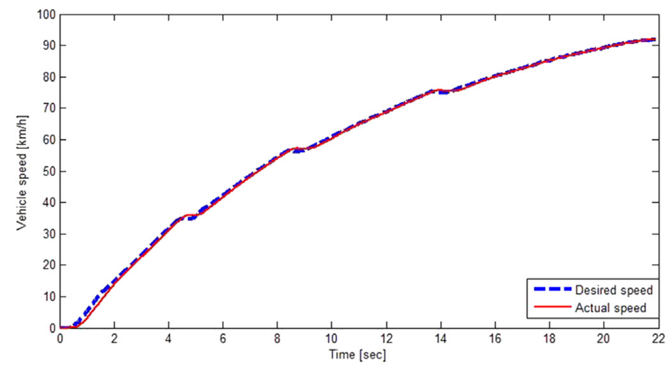

Fig. 20. Experimental and simulated hybrid FC/battery vehicle velocity responses.

the FC provides the motor with the required power most of the time. The battery contributes only when the FC can not provide needed power and when the power is negative, that is when the vehicle is decelerating. Fig. 19 shows that the SOC is regulated successfully during the whole cycle.

5. Results and discussion

The performance of the developed hybrid FC/battery vehicle model, utilizing different driving cycles, is presented in Table 7. It is clear that the vehicle performance with the Amman driving cycle differs from that with the other driving cycles examined for this study. Furthermore, when comparing the model performance of the ICE vehicle (Table 5) with that of the hybrid FC/battery vehicle (Table 7), the hybrid fuel cell vehicle is seen to be 48.5% better in terms of fuel economy with 4.59 L/100 km when compared with 8.92 L/100 km for the ICE vehicle. In addition, the hybrid FC/battery produces zero emissions of CO_2, while the emitted amount of CO_2 by the ICE vehicle is 211.1 g km^{-1}. As expected, the overall system efficiency of the hybrid vehicle is 144% better than the efficiency of the ICE version. As shown in Table 7, the recovered braking energy at the battery is 61.7% of the available total braking energy. This certainly improves the overall system efficiency. Finally, the speed tracking error of the hybrid FC/battery is much better than that of the ICE vehicle. Fig. 20 shows the velocity response of the hybrid FC/battery model when tested against experimental acceleration data. It is clear that the hybrid FC/battery vehicle is able to accelerate and track the velocity accurately. In fact, the hybrid vehicle accelerates in a better way than the ICE vehicle. One of the main differences between the hybrid FC/battery vehicle and the electrical vehicle is that the battery may be charged without being plugged-in to the grid and hence it is possible for the battery system in the hybrid FC/battery configuration to regulate its SOC about a desired value independently of any external source. As shown in Fig. 19, the battery SOC is regulated correctly about 70%.

Table 7
Performance of the Hybrid FC/battery vehicle with different driving cycles.

Driving cycle	Amman	Indian urban	New York urban	Japan 10	France INRETS urban
Fuel economy gasoline equivalent (L/100 km)	4.59	3.24	5.5	3.98	4.91
Time the trace is missed by 2 mph (%)	0.97	12.73	30.63	4.91	29.89
Absolute average difference on vehicle speed (km h^{-1})	0.31	0.08	0.15	0.06	0.15
Initial SOC %	70	70	70	70	70
Final SOC %	74.5	78.83	69.52	72.35	77.58
Powertrain bidirectional path efficiency (%)	44.8	42.09	37.27	40.39	41.02
Percentage braking energy recovered at battery (%)	61.7	64.08	52.16	79.08	46.63
CO_2 emission (g km^{-1})	0	0	0	0	0

6. Conclusions

In this study, an ICE vehicle model was developed and validated against experimental data that was recorded from a testing vehicle (taxi) running in the streets of Amman city, the capital of Jordan. This ICE model was then converted into an equivalent hybrid FC/battery vehicle model by replacing only the powertrain and keeping all other parts the same. The main components of a hybrid FC/battery powertrain are an electrical motor, a FC, and a battery. These three main components were selected and sized such that drivability, fuel economy, and emission conditions were satisfied. Different combinations of battery cells and fuel cell capacities were investigated to seek the optimum performance for the hybrid vehicle model. It was found that the hybrid FC/battery vehicle model with a 60 kW FC capacity and 120 battery cells achieved the optimum performance that satisfied all requirements. In order to investigate the effect of replacing ICE vehicles with hybrid FC/battery vehicles, the Amman driving cycle and other worldwide driving cycles were used to evaluate the performance of both types of vehicles. The simulation results, presented in this study, confirmed that hybrid FC/battery vehicles have superior performance in terms of fuel economy, drivability, emissions, and efficiency, when compared with ICE vehicles.

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